SIR-C Polarimetric Radar Results from the Weddell Sea, Antarctica

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Polarimetric radar data acquired by SIR-C in the Eastern Weddell Sea have been analyzed to investigate techniques for discriminating thin, recently formed sea-ice from thicker first year ice and open water. Several different parameters from both the L-band and the C-band have been studied to understand the scattering processes for different forms of ice. Results indicate that it is possible to differentiate between all the primary ice types appearing in the area (except between brash ice and deformed first year ice) by comparing a combination of two or three of the studied parameters. Several different combinations can be used, but the best results are found when the L-band VV-polarized backscatter and HH- and VV-pol correlation coefficient, and the co-pol ratio HH/VV in C-band are combined. Thanks to the high quality of the SIR-C data, small differences are observed which make it possible to discriminate at least two distinctive thin ice sub-groups. This increases the possibility to use these data to study how new ice evolves under these unique Southern Ocean conditions.

INTRODUCTION

The first spaceborne polarimetric radar data of Southern Ocean sea ice were acquired by SIR-C in the Eastern Weddell Sea at maximum winter ice extent during October, 1994. Despite the low (57 deg.) orbit inclination of Space Shuttle Endeavor, several orbital passes were acquired over the target site in which the incidence angle and the right-looking (i.e. south-looking) radar combined favorably to enable imaging of sea ice in the C- and L-band polarimetric mode of the SIR-C instrument.

Sea ice influences both the regional and the global climate through its effects on the heat transfer between the atmosphere and the ocean. Especially the early phase of ice growth plays a significant role in controlling how large the fluxes of heat, salt and vapor are at the surface of the ocean. For this reason it was decided to emphasize the study of thin ice. One of the major problems with single-channel microwave techniques is their poor discrimination between open water and new ice. With a polarimetric, multi-frequency system like SIR-C, the number of parameters that can be used for this classification are significantly increased.

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In this study, L- and C-band scenes covering four different regions were chosen from datatake 55.80. Three of the locations are at the inner edge of the marginal ice zone and cover areas where various types of first year ice can be found. The fourth location was chosen at the ice edge to get some comparison areas with open water and brash ice. The scenes were acquired on October 3, 1994 (Day 276). Their locations and times are listed in Table 1.

THEORETICAL BACKGROUND

Seven polarimetric parameters have been studied at both frequencies to find differences between the major ice types found at each scene location. SIR-C Multi Look Complex (MLC) quad-pol data containing cross-products of the scattering matrix have been used to extract the following parameters:

Backscattering coefficients:

$$Ahh = \langle ShhShh^* \rangle; \quad Ahv = \langle ShvShv^* \rangle; \; Avv = \langle SvvSvv^* \rangle.$$

Ratios of the copolarized and cross polarized returns:

$$r_{HH/VV} = \frac{\langle ShhShh^* \rangle}{\langle SvvSvv^* \rangle} \quad ; \qquad r_{HV/HH} = \frac{\langle ShvShv^* \rangle}{\langle ShhShh^* \rangle}.$$

Correlation coefficient between co-pol channels:

$$\rho_{HHVV} = \left| \frac{\langle ShhSvv^* \rangle}{\sqrt{\langle ShhShh^* \rangle \times \langle SvvSvv^* \rangle}} \right| .$$

Phase difference between the co-pol channels:

$$\phi_{HH-VV} = \operatorname{atan}\left(\frac{\mathrm{Im}\langle ShhSvv^* \rangle}{\mathrm{Re}\langle ShhSvv^* \rangle}\right),$$

where * denotes the complex conjugate, and < > denotes the ensemble averages of a number of pixels. Re and Im indicate the real and imaginary parts respectively within a sample box.

Table 1: Scene locations given for image centers

Latitude	**Longitude**	**GMT**
58 deg. 17.1’ S	20 deg. 17.0’ E	1994/276:20:17:04
58 deg. 13.6’ S	21 deg. 34.7’ E	1994/276:20:17:15
58 deg. 7.3’ S	23 deg. 25.0’ E	1994/276:20:17:30
57 deg. 26.8’ S	30 deg. 26.6’ E	1994/276:20:18:29

For the co-pol ratio, simulated values for pure ice and sea water have been used for comparison. The simulations are made using a Bragg scattering model for first order rough-surface scattering. These estimated values apply in cases where the surface height variations are small compared with the wavelength [1]. This implies that simulations are most representative of open water under relatively calm wind conditions and smooth ice types like undeformed new ice and thicker level first year ice. The co-pol ratio $r_{HH/VV}$ is independent of the surface roughness power spectrum and depends on the dielectric constant ε_r and the incidence angle θ_i. Increasing θ_i or ε_r should result in decreasing $r_{HH/VV}$. As long as the Bragg scattering model applies, all values of the co-pol ratio for sea ice should fall within the limits set by open water and pure ice. Signatures from open water are greatly affected by the prevailing wind-speed at the time when the images were acquired. The basic radar scattering is caused by Bragg resonance from short wavelength gravity or capillary waves. Stronger wind gives a rougher surface and thereby higher backscatter. No in-situ measurements of wind or ice conditions are available for October 3, 1994, but approximate wind-speed calculations from pressure charts give values around 8 m/s at the ice surfaces and probably a little bit higher over open water. These are consistent with estimates of windspeed made from VV sigma nought at C-band.

ANALYSIS OF DATA

Four ice types were chosen for this study:

-Thin first year ice (TFY) covering all types of recently formed ice found in leads and polynyas.

- Smooth first year ice (SFY) which is thicker and older FY ice with a level, undeformed surface that gives it a fairly dark appearance at our frequencies.
- Deformed first year ice (DFY) here denoting thick first year ice with rough or deformed surface which gives large backscatter and thereby makes it look brighter than SFY.
- Brash ice which is accumulations of ice fragments giving very high backscatter values and appearing much brighter than the surrounding open water.

To these four were added open water (OW) which hereinafter will be considered being one of the surface types. No old ice or icebergs are observed in the studied region. Further studies of the scenes revealed that the TFY ice type could be easily divided into several interesting subgroups. However, some of them were only found in a few locations, so in this paper the study will be limited to three subgroups:

- TFY ice type a (TFYa) are areas in leads that show great resemblance to open water.
- TFY ice type b (TFYb) are the darkest areas found in the scenes and have backscatter values close to the noise floor.
- TFY ice type c (TFYc) were chosen to bridge the gap between the more extreme values of type a and b.

105 L-band and 98 C-band samples have been used in this study. As expected, the co-pol ratios for samples from OW and the thin ice types fall between the simulated limits, while the rougher ice types have higher values, indicating that the Bragg scattering is no longer valid. In order to find a good combination of two or three parameters that could be used to classify of the seven chosen ice types, values for 14 of the registered parameters were compared in both L-band and C-band. It appears easier to find a good combination of parameters in the L-band than in the C-band. This is consistent with results found by Rignot and Drinkwater [2] stating that for ice mapping L-band performs better than C-band when more than one polarization is used. However, it is also possible that this result is to some extent a product of the selection process, where sample areas were chosen visually from the L-band scenes and the corresponding C-band values calculated automatically for the same area.

The best combination of two L-band parameters seems to be ρ_{HHVV} and Avv. As can be seen in Fig.1 this gives discrimination of all the ice types except for TFYa and OW and brash ice and DFY ice. If we examine Fig.1 we also find that TFYa, TFYb and TFYc follow a exponential curve for this combination of parameters. It is reasonable to assume that it would be possible to find new, young or thin FY ice in different phases all along this curve [3]. To add a third parameter would not help to separate the OW from TFYa or the brash ice from DFY ice but it would probably give a more reliable classification of the other ice types. It seems reasonable that this third parameter should be either $r_{HH/VV}$ or $r_{HV/HH}$, depending on for which ice types a better separation is required.

The best two-parameter combination for the C-band is to use $r_{HH/VV}$ together with Avv or Ahh. As can be seen in Fig.2 the biggest problem is that TFYc overlaps three other ice types. The only way we could use this is to group all three types of thin FY ice into one single ice type, suitably named TFY ice, and then use the approach with geographical separation where the scene with OW and brash is treated separately. This would leave only three ice types to classify, TFY, SFY and DFY ice. Adding the standard deviation of $\Phi_{HH\text{-}VV}$ as a third classification parameter would give a small separation

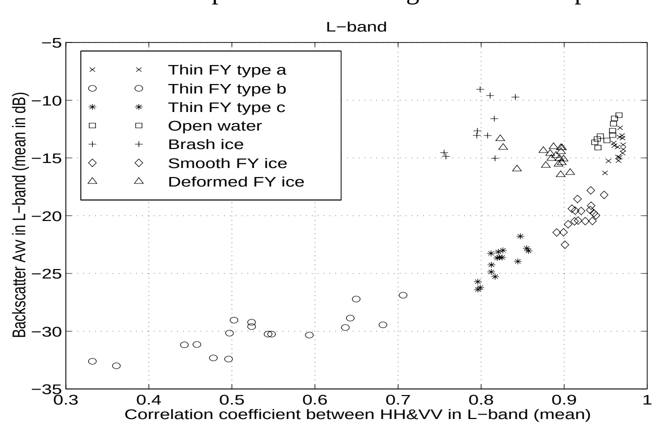

Figure 1. Best parameter combination for L-band.

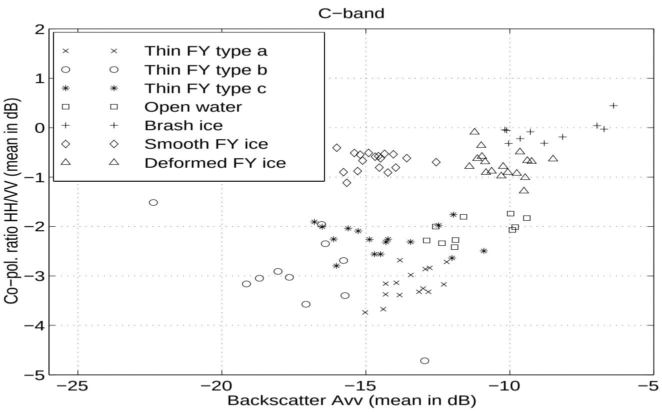

Figure 2. Best parameter combination for C-band.

between TFYa and TFYb, but would otherwise not make much difference. The only real alternative as a choice for a third parameter would be Ahv. The conclusion is that we can not get good thin ice separation with only C-band parameters.

In a multifrequency polarimetric system like SIR-C we also have the advantage of combining parameters from different frequency bands. In Fig.3 we see the results if we choose the C-band co-polarization ratio $r_{HH/VV}$ together with Avv from the L-band. $r_{HH/VV}$ give a separation between TFYa and OW, but there is still a problem distinguishing between brash ice and DFY ice. In fact, the C-band $r_{HH/VV}$ is the only parameters in this study that can unambiguously differentiate TFYa and OW, but there are no parameter in either of the bands that can give a good separation between brash ice and DFY ice. TFYb and TFYc come a little bit too close to each other, but if we take into consideration that these two most probably are different phases of the same ice type, this problem is acceptable. The reason why $r_{HH/VV}$ is higher for OW than it is for TFYa, even though TFYa is also thought to be open water, can be that the small areas of water are sheltered from wind and waves thereby having smoother surfaces. This would give higher VV backscatter compared to HH and thus lower $r_{HH/VV}$. For all other parameters, in both frequency bands, TFYa

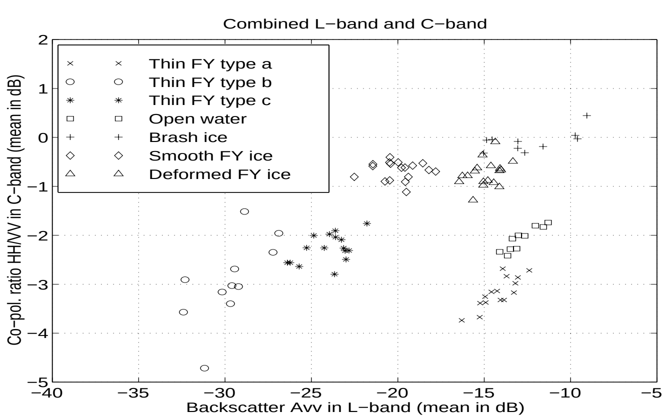

Figure 3. Combined L-band and C-band parameters.

and OW have overlapping values. This combined with some of the features seen in the images makes it reasonable to assume that TFYa in fact is calm open water and thereby should be renamed if used in future studies

CONCLUSIONS

This study shows that if TFYa is considered calm open water there are a number of different combinations of polarimetric parameters from the L- and C-band that can be used to differentiate between open water, thin first year ice and thicker first year ice. However, no combination has been found that can unambiguously separate deformed first year ice and brash ice. The most favorable candidates for the selection of the best two-parameter combination for a classifier appears to be either ρ_{HHVV} and Avv from the L-band or $r_{HH/VV}$ from the C-band paired with Avv from the L-band. Which pair of parameters to choose depends on if good separation between OW and TFYa or between TFYb and TFYc is desired. If one wants to improve the possibilities of reliable classification by using three parameters, the choice should be ρ_{HHVV} and Avv from the L-band and $r_{HH/VV}$ from the C-band. This combination can separate all seven ice types except brash ice and DFY ice.

This is a very simple approach to finding a combination of parameters for a classifier, however, it should be pointed out that only the mean values for each parameter and ice type in this study have been compared. A more thorough study will also take into consideration the distributions of the parameter values. In reality we can also expect to find ice that have parameter values that make them fall between our chosen ice types. Changed wind conditions will certainly modify the backscatter values for OW which also will affect some of its other parameters. This might cause overlapping with other ice types which are now well separated from OW in this study. Appearance of frost flowers, flooded ice, multiyear ice, icebergs or other types of ice not considered here could also be a source of confusion. As a next stop preliminary tests will be made to evaluate a classifier using the suggested combinations of parameters.

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